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A non-primordial origin for the widest binaries in the Kuiper belt

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Nearly one-third of objects occupying the most circular, coplanar Kuiper belt orbits (the cold classical belt) are binary, and several percent of them are 'ultra-wide' binaries (UWBs): ~100-km-sized companions spaced by tens of thousands of kilometres. UWBs are dynamically fragile, and their existence is thought to constrain the early Solar System processes and conditions. However, we demonstrate that UWBs can instead attain their wide architectures well after the earliest epochs of the Solar System, when the orbital migration of Neptune implants the modern non-cold, or 'dynamic', Kuiper belt population. During this implantation, cold classical belt binaries are likely to have close encounters with many planetesimals scattered across the region, which can efficiently dissociate any existing UWBs and widen a small fraction of tighter binaries into UWB-like arrangements. Thus, today's UWBs may not be primordial and cannot be used to constrain the early Solar System as directly as previously surmised.

At least ~30% of cold classical belt objects actually consist of binary systems of typically roughly equal-sized companions orbiting one another, distinguishing the cold classical belt from the rest of the Kuiper belt where these binaries are significantly rarer[1,2]. Among these binaries, perhaps 1–10% are ultra-wide binaries (UWBs), in which the two components co-orbit with semi-major axes of at least 7% of the Hill radius of the system (although lower UWB fractions are possible because observing biases favour the discovery of easily resolved, wide binaries[3–5]). Due to their extreme companion separations, UWBs are dynamically fragile, and UWB companions can be dissociated through moderately close ($\lesssim$1 Neptunian Hill radius) encounters with Neptune[6,7], impacts with approximately kilometre-scale trans-Neptunian objects (TNOs)[8,9] and close (<1 system Hill radius) gravitational encounters with other large TNOs[8,10]. Although they are relatively rare, the existence of UWBs and their susceptibility to disruption have been leveraged to constrain their minimum proximity to Neptune in the early Solar System[6] and the number of approximately kilometre-sized TNOs residing in the modern Kuiper belt[9]. In addition, the mutual orbits of TNO binaries have been used to constrain the distribution of angular momentum within planetesimal-forming clumps of pebbles in the early Solar System, and generating the widest binaries is a challenge for planetesimal formation models[11–13].

A critical implicit assumption upon which these constraints rest is that UWB orbital architectures are in fact primordial. However, past studies have shown that UWBs can be derived via the expansion of the semi-major axes of more tightly bound binaries through repeated impacts with small TNOs[5,9], as well as close impulse-delivering passages of larger TNOs, because these random impulses drive diffusion in binary orbital energy[10]. Nonetheless, significant UWB production in this manner requires a number of passing/impacting TNO bodies that are well in excess of the population estimates of the modern Kuiper belt[9,10].

However, this population discrepancy may not invalidate the non-primordial UWB production mechanism. While the cold classical belt likely formed in situ and is indefinitely stable, the same cannot be said for much of the rest of the Kuiper belt[14,15]. Over time, the orbits of some objects occupying the detached, resonant, scattering and hot Kuiper belt populations[16] (which we group together as a 'dynamic' Kuiper belt) diffuse until they begin strongly interacting with the giant planets, and they are ultimately ejected from the Solar System or trapped in the Oort cloud[17–19]. Thus, the population of the dynamic Kuiper belt is smaller today than ever, and its time-averaged value over the history of the Solar System must be higher than the modern one.

In addition, it is generally thought that the dynamic Kuiper belt is derived from a primordial belt of planetesimals whose population was approximately two to three orders of magnitude greater than that of the modern Kuiper belt[20,21]. As Neptune migrated away from

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the Sun and through this primordial belt, some of these belt members became trapped in the modern dynamic Kuiper belt, but this process was extremely inefficient[22]. All but 0.1–1% of the primordial belt objects are ejected or trapped in the Oort cloud during this process. However, the removal of a primordial belt object typically takes at least tens of million years (Myr), during which these eventually lost objects spend much of their time crossing the cold classical belt. This again suggests that the time-averaged number of TNOs crossing the cold classical belt may be substantially higher than that implied from modern observations. Thus, a previous study on the widening of TNO binaries may have greatly under-estimated the effect because they did not consider the larger numbers of TNOs in earlier epochs[10].

This is confirmed by Fig. 1. Here, we analysed the time-varying distribution of orbits within 4 billion years (Gyr) of numerical simulation of the Kuiper belt formation, which includes our inner three giant planets on their modern orbits, while Neptune migrates from 24 to 30 au (refs. 23). We used the orbital distribution of this simulation to estimate the expected encounter rate between the simulation bodies and members of the cold classical Kuiper belt at any given simulation time[10,24,25]. In Fig. 1a, we plotted the encounter rate relative to the encounter rate implied at the end of the simulation (which we assumed is analogous to the modern Kuiper belt). During the first 35 Myr of the simulation, the encounter rate is over 100 times greater than the modern one. Moreover, it remains elevated by an order of magnitude for another 200 Myr and is at least double the modern encounter rate of ~1 Gyr. Although many of the bodies that transiently cross the cold classical belt do so at higher inclinations, which decreases their individual encounter probabilities, the probabilities are still significant[25,26], and the number of such bodies is large compared to the modern dynamic Kuiper belt. This greatly enhances the number of close encounters that a binary is expected to undergo. Figure 1b plots the cumulative encounter flux, and we see that half of all expected encounters should occur during the first 100 Myr of Solar System history when the Kuiper belt has orbital properties that are very different from today's. This led to variations in the encounter velocity distribution, as shown in Fig. 1c. Here, we see that the median encounter velocity exceeds 2 km s^{-1} for much of the first billion years, which is well above the 1 km s^{-1} encounter velocities assumed in previous studies[5,8,9]. Thus, considering the long-term evolution of the Kuiper belt is critical when modelling the dynamic evolution of UWBs.

Results

To simulate the effects of a time-varying Kuiper belt on TNO binary dynamics, we subjected binaries to 4 Gyr worth of flybys from a diachronic population of TNOs, based on Fig. 1. Time 0 in all of our simulations denotes the completion of giant planet formation and gas disk dispersal in the outer Solar System. Our binaries are given orbits characteristic of a cold classical belt object at 44 au semi-major axis and no eccentricity or inclination. An example of such a simulation is shown in Fig. 2a. Here, a TNO binary begins with a semi-major axis (average separation of the companions) that is 3.5% of its Hill radius, which is half the minimum separation necessary for UWB classification. After ~500 Myr of close TNO passages, its mutual semi-major axis widened to 9% of its Hill radius, placing it firmly within the UWB regime and quite similar to 2006 JZ$_{81}$, a known UWB[4]. After another ~500 Myr, its semi-major axis expanded to 15%, near that of the known UWB 2000 CF$_{105}$ (ref. 27). Following another expansion to a semi-major axis nearly like the widest UWB, 2001 QW$_{322}$ (ref. 28), additional TNO flybys further expanded the binary semi-major axis until it became unbound after ~2 Gyr. Figure 2b,c shows that these flybys (as well as the solar influence) also drive large changes in the eccentricity and inclination of the binary. Thus, Fig. 2 documents that a tight TNO binary predicted by past studies to be indefinitely stable actually transforms into a UWB within 200 Myr and is completely dissociated in less than half the age of the Solar System.

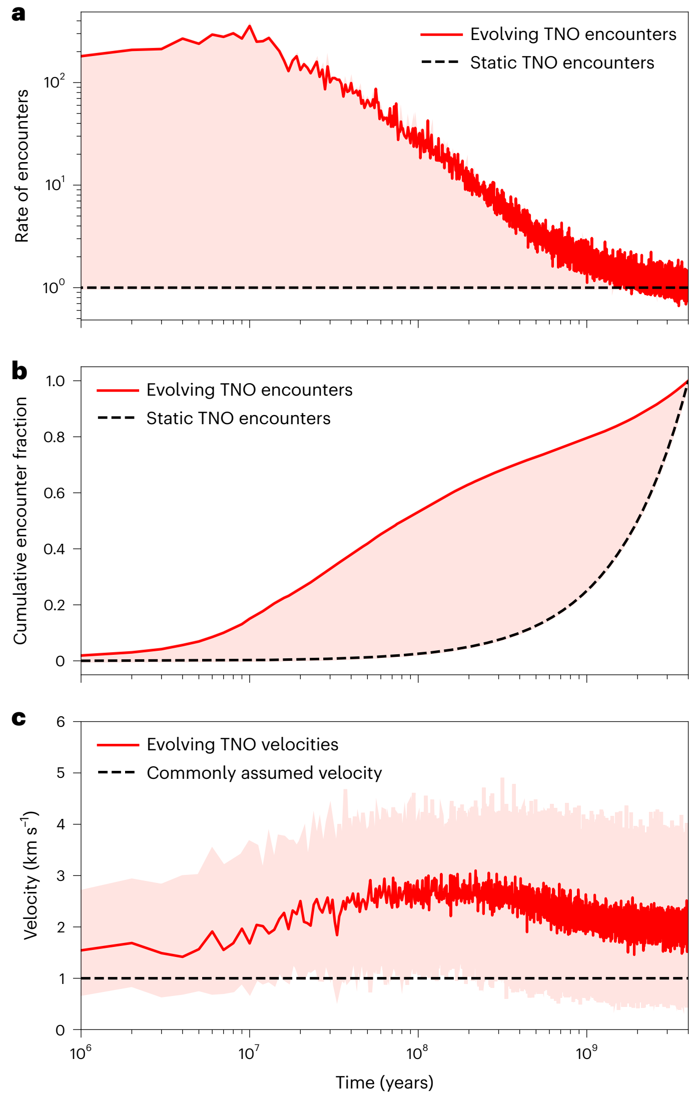

Fig. 1 | Changes in the TNO-encountering population over time. a, Predicted rate of TNO encounters for a cold classical body as a function of time inferred from a simulation of Kuiper belt formation[23] (red curve). The predicted rate is plotted and normalized relative to a fixed rate inferred by the end state of the simulation (dashed line), and the shaded region highlights the excess encounters predicted relative to the assumption of a non-evolving Kuiper belt. **b**, Cumulative flux of TNO encounters for a cold classical body as a function of time inferred from the Kuiper belt formation simulation (red curve). The cumulative flux is also shown for a static Kuiper belt inferred from the end state of the simulation (dashed curve), and the difference between the two is shaded. **c**, Median TNO encounter velocity for a cold classical body as a function of time inferred from the Kuiper belt formation simulation (red curve). The shaded region spans the 5th to 95th encounter velocity percentiles, and the dashed line marks the 1 km s^{-1} velocity assumed in prior studies of TNO binary dynamics[5,9].

We found that the widening of tighter TNO binaries into UWB arrangements was not uncommon in our simulations. The differential velocity impulses that our flybys impart on binary companions often decrease the gravitational binding of binary orbits and can ultimately unbind them. Such behaviour is expected when binaries are subject to gravitational encounters with low-mass bodies passing at velocities much higher than the binary orbital velocity[29,30], although semi-major axis decreases are also possible (see Section 1.6 of the Supplementary Information). In Fig. 3, we plot the distribution of binary semi-major axes sampled during the last billion years of a simulation, in which 1,000 binaries with initial semi-major axes of 3–5% of their Hill radii are subjected to 4 Gyr of TNO flybys. Here, we see that ~9% of the surviving

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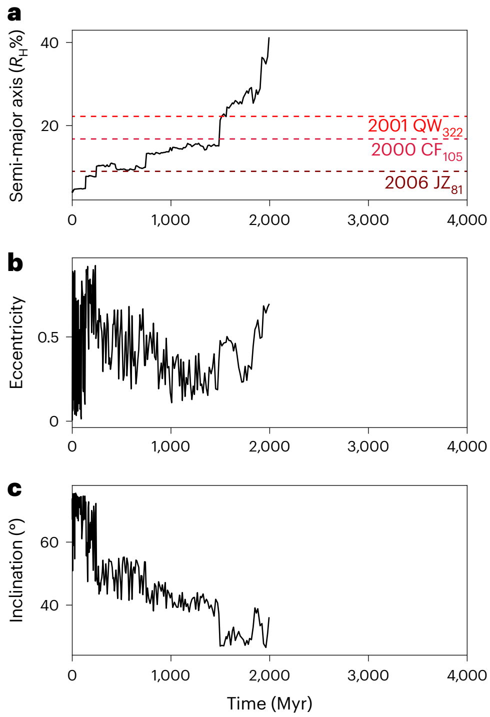

Fig. 2 | Example of binary widening. a, Evolution of the semi-major axis of an individual simulated binary over time, as it is exposed to close encounters with TNOs. The semi-major axes of the three known UWBs are indicated by dashed lines. **b**, Orbital eccentricity of the simulated binary versus time. **c**, Orbital inclination of the simulated binary (measured with respect to its heliocentric orbit) as a function of time.

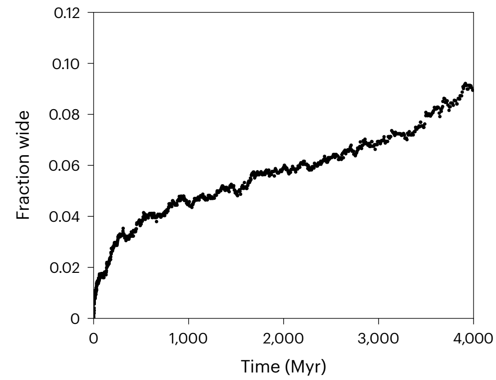

Fig. 3 | Binary widening efficiency. For 1,000 simulated binaries with initial semi-major axes between 3% and 5% of the Hill radius, the fraction of bound systems that evolve to semi-major axes over 7% of the Hill radius is shown as a function of time.

sample has semi-major axes that significantly widen beyond 0.07 Hill radii, the minimum semi-major axis of the UWB regime[4,5]. This percentage depends on the size–frequency distribution (SFD) that we assume for the dynamic Kuiper belt but among observationally favoured SFDs[31], even the one yielding the weakest set of TNO encounters still causes ~7% of initially tight binaries to widen into UWBs. (See Section 1.4 of the Supplementary Information for additional considerations of SFDs.) Thus, we should expect TNO passages to widen as many as one-tenth of moderately tight (3–5% Hill radius) binaries into UWBs over the history of the Solar System. However, this does not hold true for even tighter binaries, because systems with initial mutual semi-major axes of 1–2% Hill radius virtually never widen to UWB status (see Section 1.6 of the Supplementary Information).

Of course, our simulated UWBs generated from widened tight binaries have a distribution of orbits that can be compared with the orbits of the observed UWBs. In Fig. 4a, we compare our simulated UWB semi-major axes with those from the nine known UWB systems[4,32]. We see that the distributions look qualitatively similar, and the Kolmogorov–Smirnov (K-S) test comparing the two distributions returns a *P* value of 0.09, indicating that we cannot reject the null hypothesis that the two distributions sample the same underlying distribution with 2-σ confidence.

We can similarly compare the eccentricity distributions of the simulated and observed UWBs. In this case, our initial conditions are designed to explicitly test whether the observed UWBs can be derived from tighter binaries, because our initial binary eccentricity distribution is simply the observed eccentricities for non-UWB binaries[32]. It is well known that UWBs have hotter eccentricities than non-UWBs, but they are also cooler than a thermalized distribution ($\langle e \rangle \simeq 0.7$) (refs. 4,32). In Fig. 4b, we show the eccentricity distribution of UWBs in our simulations that are generated from the gradual widening of tighter binary systems. The simulated and observed distributions appear similar, and a K-S test returns a *P* value of 0.94, indicating that the statistical differences in these two distributions are not significant enough to rule out the generation of UWB eccentricities through the widening of tighter, less eccentric binaries.

We also compared the inclinations of the simulated and observed UWBs in Fig. 4c. Once again, it has been posited that the observed UWBs have a different inclination distribution than tighter binaries, with UWBs exhibiting a greater paucity of polar orbits[4,32]. With a sample size of only nine observed UWBs, it is not clear that this observed difference is statistically significant because a K-S test comparing the two observed distributions yields a *P* value of 0.28. Nevertheless, if we begin with 1,000 tight binaries with the observed tighter inclination distribution, Fig. 4c shows that the simulated UWBs that we generated possess fewer polar orbits than the tighter binaries. This appears to be an effect of the Kozai–Lidov mechanism[33,34]. The Kozai–Lidov cycles drive binaries to large eccentricities (and large apocentre) at the minimum inclination of the cycle. Thus, binaries during a Kozai cycle have larger average separations at their low inclinations, which allows TNO passages to deliver stronger impulses during this phase, enhancing the probability that UWBs will be generated at such inclinations. Although the decrease in polar orbits is much less dramatic among our simulated UWBs, we again stress that the observed UWB sample consists of only nine systems, and a K-S test comparing the simulated and observed UWBs cannot reject the null hypothesis with 2-σ confidence ($P = 0.34$).

Finally, we can use our simulations to study the survival of hypothetically primordial UWBs throughout the entire evolution of the Kuiper belt. To do this, we assembled 1,000 binaries with initial system masses and semi-major axes matching 2001 QW_{322} and subjected them to 4 Gyr worth of TNO passages. The surviving fraction, as a function of time, is shown in Fig. 5. Here, it can be seen that the large majority is dissociated over the history of the Solar System because only 5.1% reaches the end of the simulation. However, despite the fact that most binary evolution is towards increased separation, the vast majority of surviving binaries persist by decreasing separation. Smaller semi-major axes help shield them from TNO passage effects, and most such binaries reach the end of the simulation because they evolve to a smaller semi-major axis (<0.8 of their original value, roughly the same separation as 2000 CF_{105}, the next widest binary). Only 1.7% of our binaries finish with semi-major axes that are greater than or equal to 0.8 of the semi-major axis of 2001 QW_{322} (0.22 Hill radius). The rate of destruction is again dependent on our assumed dynamic SFD, but among observationally favoured SFDs[31], our weakest encounter sets still yield only 2.5% of binaries with final semi-major axes beyond 80% of 2001 QW_{322}. This implies that if the binary orbit of 2001 QW_{322} is indeed primordial, it is the remnant of a primordial population that is ~40–60 times greater than today's population.

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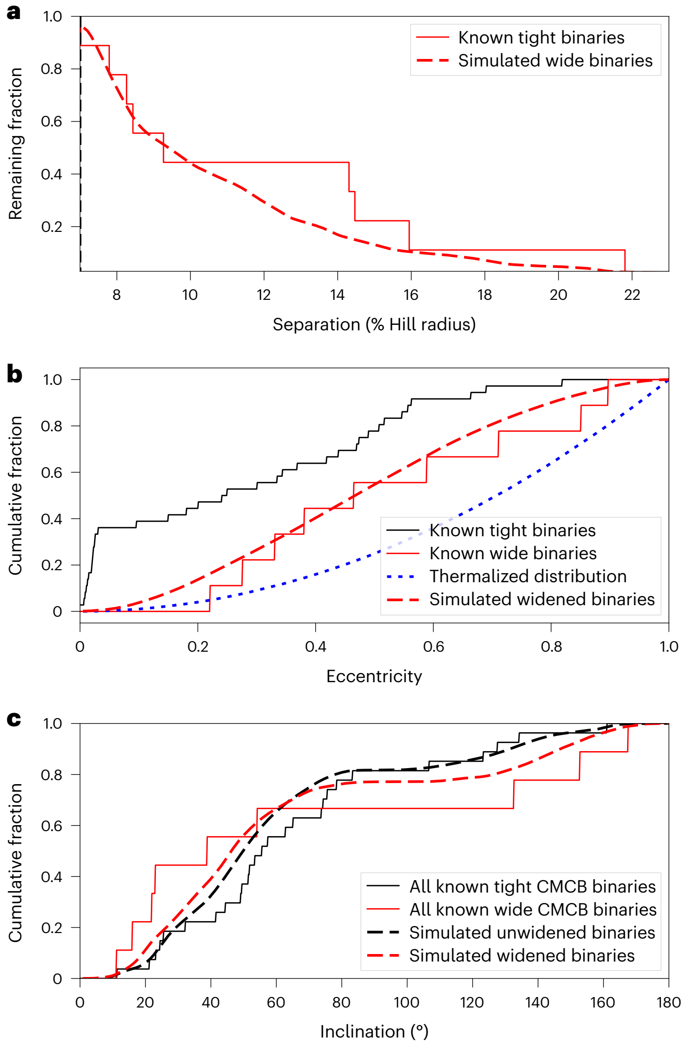

Fig. 4 | Orbital distributions of widened binaries after 4 Gyr. a, Distribution of the semi-major axes of simulated (dashed) UWBs formed through the widening of tight binaries is compared against the observed (solid) distribution of UWB semi-major axes. **b**, Distribution of the eccentricities of simulated (dashed) UWBs formed through the widening of tight binaries is compared against the observed (solid) distribution of UWB eccentricities. The thermal eccentricity distribution is also shown (dotted). **c**, Distribution of the binary inclinations of simulated (dashed red) UWBs formed through the widening of tight binaries is compared against the observed (solid red) distribution of UWB eccentricities in the cold main classical belt (CMCB). The simulated (dashed black) and observed distributions (solid black) for the non-UWB binaries are also shown.

Discussion

Most previous studies have under-estimated the orbital evolution and instability of TNO binaries. This can be attributed to two reasons. First, more attention and modelling have been devoted to considering the effects of velocity impulses from collisions with small TNOs rather than close encounters with TNOs. Although collisions can indeed alter the orbital evolution of TNO binaries, the magnitude of the collisional impulse does not depend on the binary orbital architecture. This is not true for TNO close encounters, in which the perturbation effectively results from a tidal force and binaries with larger separations experience larger perturbations. Thus, a sequence of close encounters on a binary has the potential for a stronger multiplier effect, wherein the effects of later encounters are more dynamically consequential for binary evolution if early encounters result in some degree of binary widening.

Second, the total population of the dynamic Kuiper belt has decreased substantially as the Solar System has aged. Objects within the cold classical belt experienced close TNO encounters at a much higher rate in the early Solar System epochs than in the modern epoch. Thus, the total number of encounters that TNO binaries have suffered is substantially higher than that implied by the static backward projection of modern Kuiper belt conditions.

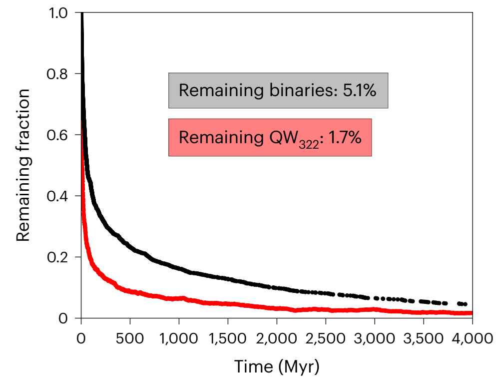

Fig. 5 | Destruction of primordial UWBs. The fraction of the simulated 2001 QW_{322} binaries that remained as a function of time. The black curve represents all bound binaries and the red curve represents only binaries with a semi-major axis of at least 80% of that observed for 2001 QW_{322}.

Our simulations show that if the widest UWB orbits are in fact primordial, then they are remnants of a much larger primordial binary population that has largely been dissociated via impulses from TNO passages. Because these dissociated members would be a major contributor to today's population of single objects within the cold classical belt, this primordial origin scenario may conflict with the observation that cold classical singles have a distinctly redder colour distribution than cold classical binaries[35]. In particular, of the 83 cold classical singles with accurate colour measurements, only two (2.4%) had spectral slopes below 17%, whereas 8 of 30 (27%) cold classical binaries had such flat slopes. These notably flat-sloped binaries include 2001 QW_{322}, which should now accompany many flat-sloped single counterparts if the binary is a rare primordial survivor of TNO passages. (It would have been subject to destructive TNO passages whether Neptune dynamically pushed it out into the cold belt or if it always resided in the cold belt[36].) It is not clear how this stark discrepancy between binary and single colours could be maintained if such a large primordial UWB population existed and most was subsequently converted into singles.

Our study showed that close TNO passages expand the orbits of some tighter binaries to generate a population of UWBs with an efficiency and orbital distribution that may explain the observed population of UWBs. Thus, it is possible that the orbits of known UWBs are not primordial, and that most of these systems only attained their dynamically fragile states at least hundreds of million years after the formation of the Solar System. If this is the case, then UWB orbits do not necessarily constrain the degree of their minimum proximity to Neptune, the number of small impacting bodies in the early outer Solar System or the angular momenta of the planetesimal formation models.

Methods

Our simulations of TNO binary evolution used a modified version of the SWIFT RMVS4 integrator chosen for its ability to accurately integrate test particles through very high eccentricity[37]. We simulated the widening of 1,000 tight (3–5% Hill radius) binaries. The Hill radius here is the gravitational influence of a system orbiting at 44 au, defined identically to previous studies[9,10]. The lower bound of this separation range was chosen because there was a diminishing semi-major axis evolution below this (see Section 1.6 of the Supplementary Information), and the upper bound was chosen because it required significant semi-major axis evolution (~50% growth) for binaries to reach the UWB regime. In addition, we simulated the dynamic survival of

1,000 binaries resembling 2001 QW_{322}. Simulations were run in batches of ten massless test particles placed in orbit about a common central mass that possesses the combined mass of 2001 QW_{322}, or ~2.1×10^{18} kg (ref. 4). (See Section 1.5 of the Supplementary Information for consideration of a lower system mass.) Binary (test particle) inclinations and eccentricities were randomly drawn from the distributions observed among non-UWBs (whose inclinations resemble the predictions of recent streaming instability simulations[32,38]), and the arguments of the pericentre, longitudes of the ascending node and mean anomalies were all randomly drawn from uniform distributions. Simulations of tight binaries employ a 16-day time step (1/20 of a 3% Hill radius orbital period), and simulations of 2001 QW_{322} use a 50-day time step[10].

In addition to including the Sun in a fixed circular orbit at 44 au, each batch of ten binary systems was perturbed by a unique set of passing TNOs. The rate and velocity of such passages were determined from the 1-Myr outputs of a 'grainy slow' simulation of Kuiper belt formation that excludes a hypothetical undiscovered planet and includes the inner three giant planets on their modern orbits, as well as Neptune migrating to 30 au through a disk of test particles[23]. (An alternative 'smooth fast' formation model was considered in Section 1.3 of the Supplementary Information[39].) During each 1-Myr output, the encounter probability between the dynamic bodies of the Kuiper belt formation simulation and the observed cold classical belt, as well as the cold classical belt self-interaction[24,25], was numerically computed, in addition to the encounter speeds[10]. The total number of dynamic bodies at each Kuiper belt formation simulation step was calculated assuming that there were 250,000 dynamic bodies with magnitude $H_r < 8.66$ at time $t = 4$ Gyr in our Kuiper belt formation simulation, which matched observations[25], and then scaling accordingly. This population number was then extrapolated down to radii of 20 km using a magnitude–frequency distribution (MFD) and an assumed albedo of 0.04 (refs. 31,40). The combined influence of passing bodies with radii smaller than 20 km is far less significant than the combined influence of larger bodies[10]. The MFDs we tested had a faint-end power law index of 0.4 and a bright-end index of 0.9. We ran all of our simulations twice, differing in the point of transition between the two MFD power laws ('the knee'): once at r (radius) = 50 km and again at r = 85 km, which were both allowed by observations[31]. The MFD of our cold classical belt is an exponentially tapered power law[41], and its population size is scaled similarly over time. Finally, we assumed a bulk density of 1 g cm^{-3} to convert the passing TNO radii into masses[5,9]. In this manner, 4 Gyr of TNO encounters were generated for each batch of simulated binaries, but the inter-encounter time was shortened to increase the simulation throughput[10]. Potential collisions with smaller TNOs were not observed in the simulations. This was done to study and isolate the role of passages, but inclusion of collisions could likely enhance the dynamic behaviours we documented here[5].

Data availability

The simulation outputs necessary to replicate all figures and analyses in this work will be provided on the publicly accessible repository, Harvard Dataverse (https://doi.org/10.7910/DVN/LI1NJF). Source data are provided with this paper.

Code availability

The analysis codes necessary to replicate all figures and analyses in this work will be provided on the publicly accessible repository, Harvard Dataverse (https://doi.org/10.7910/DVN/LI1NJF). Our numerical simulation source code is available at https://github.com/nathankaib/Swift_KBOBin.

References

1. Noll, K. S., Grundy, W. M., Stephens, D. C., Levison, H. F. & Kern, S. D. Evidence for two populations of classical transneptunian objects: the strong inclination dependence of classical binaries. *Icarus* **194**, 758–768 (2008).
2. Noll, K., Grundy, W. M., Nesvorný, D. & Thirouin, A. in *The Trans-Neptunian Solar System* (eds Prialnik, D. et al.) 201–224 (Elsevier, 2020).
3. Lin, H. W. et al. On the detection of two new trans-Neptunian binaries from the CFEPS Kuiper Belt Survey. *Publ. Astron. Soc. Pac.* **122**, 1030–1034 (2010).
4. Parker, A. H. et al. Characterization of seven ultra-wide trans-Neptunian binaries. *Astrophys. J.* **743**, 1–22 (2011).
5. Brunini, A. & Zanardi, M. Dynamical and collisional evolution of Kuiper belt binaries. *Mon. Not. R. Astron. Soc.* **455**, 4487–4497 (2016).
6. Parker, A. H. & Kavelaars, J. J. Destruction of binary minor planets during Neptune scattering. *Astrophys. J. Lett.* **722**, L204–L208 (2010).
7. Stone, L. R. & Kaib, N. A. Evolution of primordial Kuiper belt binaries through a giant planet instability. *Mon. Not. R. Astron. Soc.* **505**, L31–L35 (2021).
8. Petit, J. M. & Mousis, O. KBO binaries: how numerous were they? *Icarus* **168**, 409–419 (2004).
9. Parker, A. H. & Kavelaars, J. J. Collisional evolution of ultra-wide trans-Neptunian binaries. *Astrophys. J.* **744**, 139–152 (2012).
10. Campbell, H. M., Stone, L. R. & Kaib, N. A. Close trans-Neptunian object passages as a driver of the origin and evolution of ultrawide Kuiper belt binaries. *Astron. J.* **165**, 19–29 (2023).
11. Youdin, A. N. & Goodman, J. Streaming instabilities in protoplanetary disks. *Astrophys. J.* **620**, 459–469 (2005).
12. Johansen, A. et al. Rapid planetesimal formation in turbulent circumstellar disks. *Nature* **448**, 1022–1025 (2007).
13. Nesvorný, D. et al. Binary planetesimal formation from gravitationally collapsing pebble clouds. *Planet. Sci. J.* **2**, 27–47 (2021).
14. Lykawka, P. S. & Mukai, T. Long term dynamical evolution and classification of classical TNO_s. *Earth Moon Planets* **97**, 107–126 (2005).
15. Dawson, R. I. & Murray-Clay, R. Neptune's wild days: constraints from the eccentricity distribution of the classical Kuiper belt. *Astrophys. J.* **750**, 43–71 (2012).
16. Gladman, B., Marsden, B. G. & Vanlaerhoven, C. in *The Solar System Beyond Neptune* (eds Barucci, M. A. et al.) Ch. 3 (Univ. of Arizona Press, 2008).
17. Oort, J. H. The structure of the cloud of comets surrounding the Solar System and a hypothesis concerning its origin. *Bull. Astron. Inst. Neth.* **11**, 91–110 (1950).
18. Levison, H. F. & Duncan, M. J. From the Kuiper belt to Jupiter-family comets: the spatial distribution of ecliptic comets. *Icarus* **127**, 13–32 (1997).
19. Duncan, M. J. & Levison, H. F. A scattered comet disk and the origin of Jupiter family comets. *Science* **276**, 1670–1672 (1997).
20. Malhotra, R. The origin of Pluto's orbit: implications for the Solar System beyond Neptune. *Astron. J.* **110**, 420–429 (1995).
21. Levison, H. F., Morbidelli, A., van Laerhoven, C., Gomes, R. & Tsiganis, K. Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune. *Icarus* **196**, 258–273 (2008).
22. Nesvorný, D. Evidence for slow migration of Neptune from the inclination distribution of Kuiper belt objects. *Astron. J.* **150**, 73–90 (2015).
23. Anderson, K. E. & Kaib, N. A. Signatures of a distant planet on the inclination distribution of the detached Kuiper belt. *Astrophys. J. Lett.* **920**, L9–L14 (2021).
24. Petit, J. M. et al. The Canada–France Ecliptic Plane Survey—full data release: the orbital structure of the Kuiper belt. *Astron. J.* **142**, 131 (2011).
25. Abedin, A. Y. et al. OSSOS. XXI. Collision probabilities in the Edgeworth–Kuiper belt. *Astron. J.* **161**, 195–207 (2021).

26. Dell'Oro, A., Campo Bagatin, A., Benavidez, P. G. & Alemañ, R. A. Statistics of encounters in the trans-Neptunian region. *Astron. Astrophys.* **558**, A95 (2013).
27. Noll, K. S. et al. Detection of two binary trans-Neptunian objects, 1997 CQ_{29} and 2000 CF_{105}, with the Hubble Space Telescope. *Astron. J.* **124**, 3424–3429 (2002).
28. Petit, J. M. et al. The extreme Kuiper belt binary 2001 QW_{322}. *Science* **322**, 432–434 (2008).
29. Heggie, D. C. Binary evolution in stellar dynamics. *Mon. Not. R. Astron. Soc.* **173**, 729–787 (1975).
30. Bahcall, J. N., Hut, P. & Tremaine, S. Maximum mass of objects that constitute unseen disk material. *Astrophys. J.* **290**, 15–20 (1985).
31. Lawler, S. M. et al. OSSOS. VIII. The transition between two size distribution slopes in the scattering disk. *Astron. J.* **155**, 197–205 (2018).
32. Grundy, W. M. et al. Mutual orbit orientations of transneptunian binaries. *Icarus* **334**, 62–78 (2019).
33. Kozai, Y. Secular perturbations of asteroids with high inclination and eccentricity. *Astron. J.* **67**, 591–598 (1962).
34. Lidov, M. L. The evolution of orbits of artificial satellites of planets under the action of gravitational perturbations of external bodies. *Planet. Space Sci.* **9**, 719–759 (1962).
35. Fraser, W. C. et al. Col-OSSOS: the distinct color distribution of single and binary cold classical KBOs. *Planet. Sci. J.* **2**, 90–95 (2021).
36. Fraser, W. C. et al. All planetesimals born near the Kuiper belt formed as binaries. *Nature* **1**, 0088 (2017).
37. Levison, H. F. & Duncan, M. J. The long-term dynamical behavior of short-period comets. *Icarus* **108**, 18–36 (1994).
38. Nesvorný, D., Li, R., Youdin, A. N., Simon, J. B. & Grundy, W. M. Trans-Neptunian binaries as evidence for planetesimal formation by the streaming instability. *Nature* **3**, 808–812 (2019).
39. Kaib, N. A. & Sheppard, S. S. Tracking Neptune's migration history through high-perihelion resonant trans-Neptunian objects. *Astron. J.* **152**, 133–147 (2016).
40. Gladman, B. et al. The structure of the Kuiper belt: size distribution and radial extent. *Astron. J.* **122**, 1051–1066 (2001).
41. Kavelaars, J. J. et al. OSSOS finds an exponential cutoff in the size distribution of the cold classical Kuiper belt. *Astrophys. J. Lett.* **920**, L28–L34 (2021).

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Author contributions

H.M.C. modified and tested the numerical binary code and oversaw the running of the simulations. K.E.A. extracted the necessary data from the Kuiper belt formation simulations. All authors contributed to the interpretation and discussion of the results and writing and editing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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